TECHNICAL MEMORANDUM

SUBJECT: Oyster recruitment failure in the Northern Gulf of Mexico as a consequence of the 2010 Deepwater Horizon Oil Spill

DATE: September 9, 2015

TO: Marla Steinhoff, NOAA; Mary Baker, NOAA

FROM: Jonathan H. Grabowski, Northeastern University; Heather M. Marrison, Jessica Murray, and Henry Roman, IEc; Shahrokh Rouhani, NewFields; and Sean P. Powers' University of South Alabama

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INTRODUCTION

The explosion of the *Deepwater Horizon* drilling platform initiated an unprecedented chain of environmental perturbations in the northern Gulf of Mexico in April 2010. The release of hundreds of millions of liters of crude oil in offshore waters and the advection and subsequent deposition of vast quantities of the released oil in sensitive nearshore habitats represented a substantial threat to the ecological integrity of the Gulf coast. Response activities such as the release of vast quantities of river water from salinity control structures east and west of the Mississippi River and efforts to clean up oil within nearshore environments negatively impacted coastal and estuarine habitats including oyster reefs, resulting in substantial oyster mortality in nearshore and subtidal environments. In addition to the direct loss due to oyster mortality in 2010, the lack of recovery observed during NRDA surveys after the spill from 2011 to 2014 suggests that recruitment failure has occurred in this region following the DWH spill (Exhibit 1; Powers et al. 2015a, b). Such findings are not surprising, given the significant reductions in oyster density and widespread loss of oyster spawning stock resulting from the spill (Powers et al. 2015a, b, Grabowksi et al. 2015). For instance, compared to baseline values (average 2006-2009) in areas outside the footprint of the river water releases, the density of subtidal oysters were extremely low in 2010 in the central portion of the northern Gulf of Mexico (eastern LA through MS; Grabowski et al. 2015). In addition, river water inputs in 2010 may have altered typical reproductive patterns in Barataria Bay and Breton Sound that year, further contributing to later reproductive failure. In this memo, we estimate reproduction forgone from these spill-related impacts and express it as the quantity of market-equivalent oysters in nearshore and subtidal reef lost due to the spill.

METHODS

We estimated reproductive losses due to two direct impacts of the spill: 1) spawning stock losses due to spill-related oyster mortality in the nearshore and subtidal environments; and 2) suppressed reproduction in 2010 in areas in Louisiana waters experiencing low salinities due to river water releases initiated in response to the spill (Exhibit 2). For the spawning stock impacts, we used previously estimated nearshore and subtidal injury estimates (Powers et al. 2015a, b) to determine the lost spawning stock that occurred in Barataria Bay and Breton Sound basins (Exhibit 3) due to the spill (i.e., those areas that experienced less <5ppt for more than an additional 30 consecutive days between April 27 and September 15, 2010 as compared to the number of consecutive days below 5ppt during baseline years, 2006-2009; Rouhani and Oehrig 2015). In addition, we quantified suppressed reproduction in 2010 from regions outside the above <5 ppt footprint that experienced salinity <8 ppt daily for more than 30 total days between April 27 and September 15, 2010 (Exhibit 4; Rouhani and Oehrig 2015). We then modeled the expected reproduction forgone due to oyster mortality and spawning failure due to low salinity levels as a consequence of river water releases. We quantified the impact using estimates of adult fecundity, fertilization success, and sex ratios, as well as egg and larval survival rates from empirical Gulf of Mexico data and peer-reviewed studies of oysters and related species, as shown in Exhibit 5. As shown in Exhibit 6, we modeled lost spawning from adult (>75 mm shell height) oysters killed in 2010 (the F0 generation) as well from the two subsequent generations (F1 and F2) forgone because of the spill, and we quantified the reproduction forgone across their expected adult lifespan of 3.5 years (assuming a total maximum lifespan of five years; Powers, unpublished data). Because oysters can begin spawning before they reach 75 mm shell height, this estimate is conservative. Each year of modeling accounts for potential mortality/harvest within each of the generations of spawning adults, as illustrated in Exhibits 7 and 8. The sum of the impacts over all seven years of reproductive modeling in nearshore and subtidal environments represents the total estimate of lost reproduction due to the DWH spill. This loss is presented in terms of market-equivalent oysters based on Gulf of Mexico-specific survival estimates for spat and seed oysters, as described in Roman and Hollweg (2015).

RESULTS AND DISCUSSION

The number of adult equivalent oysters lost from impacts of the spill on oyster reproductive efforts was calculated by determining the number of eggs that were not produced by the oysters directly killed by oil and freshwater, along with the eggs not produced by surviving oysters. These lost eggs were converted to adult equivalent forgone oysters using information on the proportion that would be expected to survive and grow to adult stages. Over three generations (7 years after the spill), these oysters would have produced a total of 170-310 million pounds of fresh oyster meat (wet weight) assuming typical survival and a five year maximum lifespan.[1] Collectively, our modeling efforts estimated that between 2.8 and 5.1 billion market equivalent

[1] We apply survival probability derived from Roman and Hollweg (2015), which assumes the following:

1) production to 75 mm market-size oyster is 1.8 grams ash-free dry weight (g afdw) in subtidal and nearshore habitats; and,
2) continued survival to five years contributes an average g afdw of 1.3 g in subtidal habitat, given harvest pressure, and 2.4 g in nearshore habitat, given that nearshore oysters are not commercially harvested.

oysters were lost as a result of reproduction forgone following the DWH spill. The bulk of this loss resulted from subtidal impacts of response actions that suppressed reproduction and reduced spawning stocks in Barataria Bay and Breton Sound, but losses of approximately 61 million market-equivalent oysters were also estimated to result from spawning stock losses in the nearshore in oiled areas such as Barataria Bay and Mississippi Sound (Powers et al. 2015b*)*.

Because oyster cover is still present in the areas affected by river water releases, there is still substrate for oyster spat to eventually settle on. Field measurements of oyster spat settlement combined with modeled larval oyster movement, shoreline oiling, and mapping of areas affected by freshwater indicate that Barataria Bay, Breton Sound, and Mississippi Sound are areas where oyster reproduction has been most severely affected by the spill (Murray et al. 2015).

It should be noted that while the reproductive output of subtidal oyster populations may gradually recover over 7 years without intervention (because oyster shell cover is still present in these areas), the reproductive output of missing nearshore oysters (8.3 million adult equivalent oysters per year) would persist until restoration rebuilds spawning oysters in the intertidal zone, where oil and cleanup actions have eliminated oyster shell cover (Powers et al. 2015a, b).

Collectively, these results suggest that the impacts of the DWH Oil Spill and response activities are far greater than just the immediate impact on the survival of valuable coastal and marine species. These impacts have been demonstrated empirically by extensive yearly oyster abundance and settlement data collected by NRDA teams that shows both low densities and low or zero recruitment of spat (Powers et al. 2015a, b). These empirical observations and the magnitude of effect estimated in this memo show a prolonged and large-scale injury that threatens the viability of oyster populations throughout the northern central Gulf of Mexico, but especially in Barataria Bay and Black Bay/Breton Sound.

Exhibit 1: DWH NRDA oyster settlement rate measurements in Northern Gulf of Mexico. (a) Fall 2011 field sampling; (b) Fall 2012 field sampling; (c) Spring 2013 field sampling; (d) Spring/Summer 2014 field sampling.

(a)

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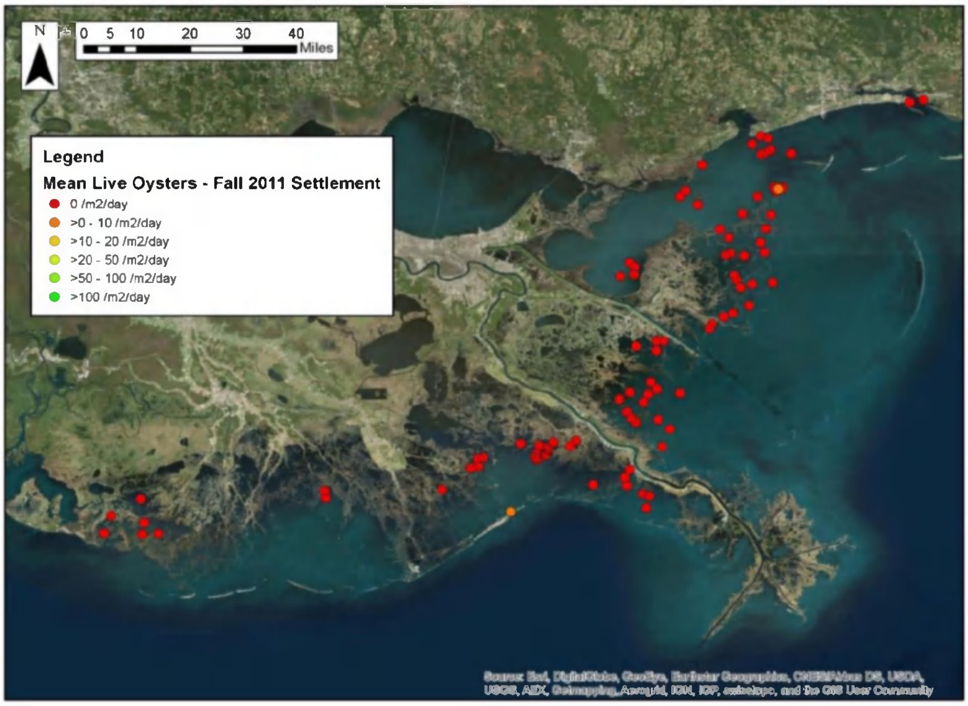
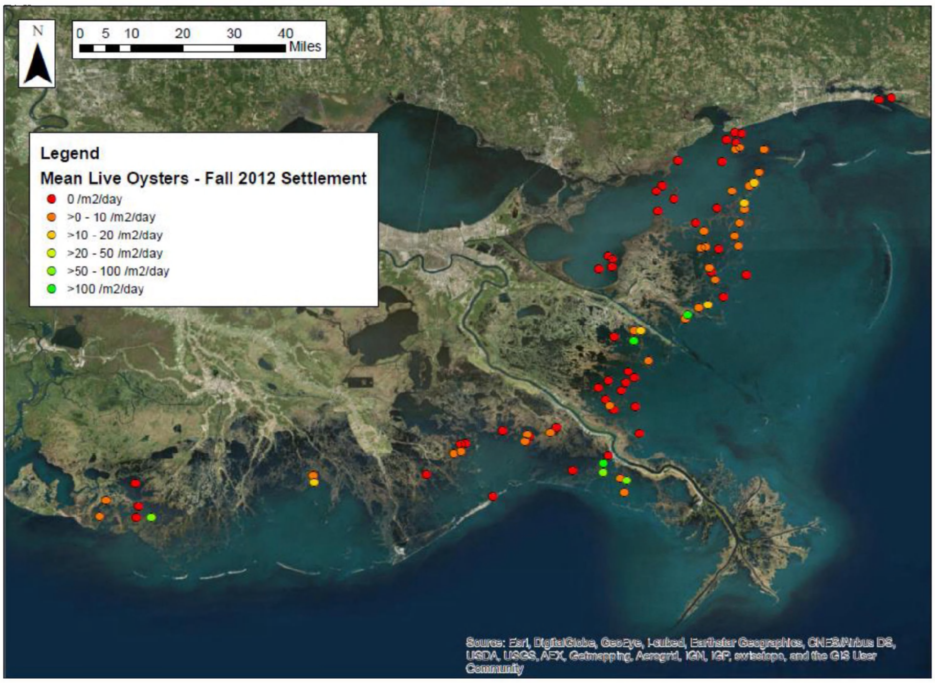


(b)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Mean Live Oysters - Fall 2012 Settlement
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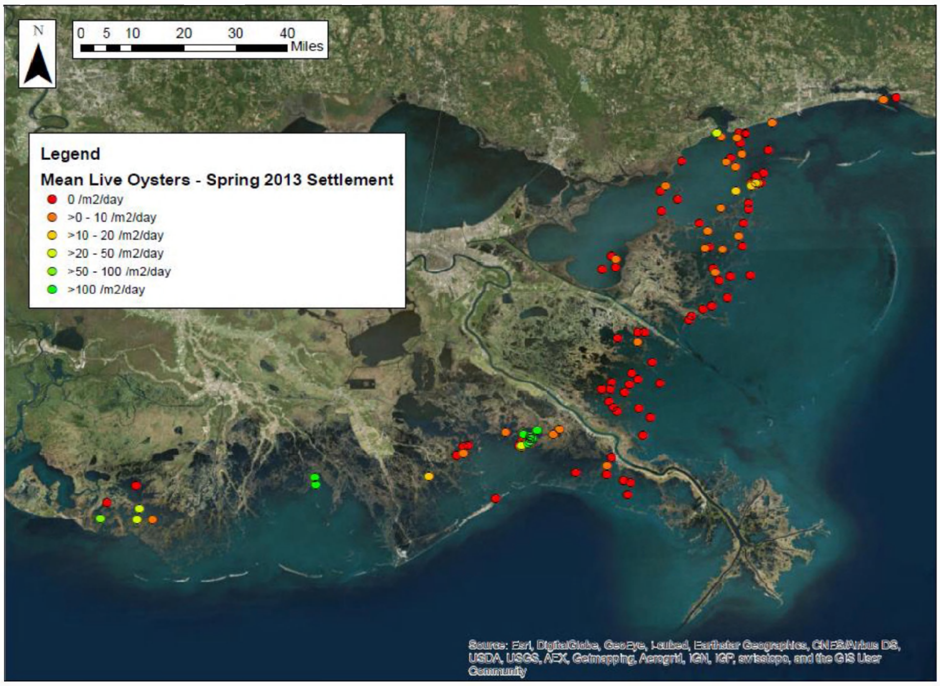
Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

(c)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Mean Live Oysters - Spring 2013 Settlement
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Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

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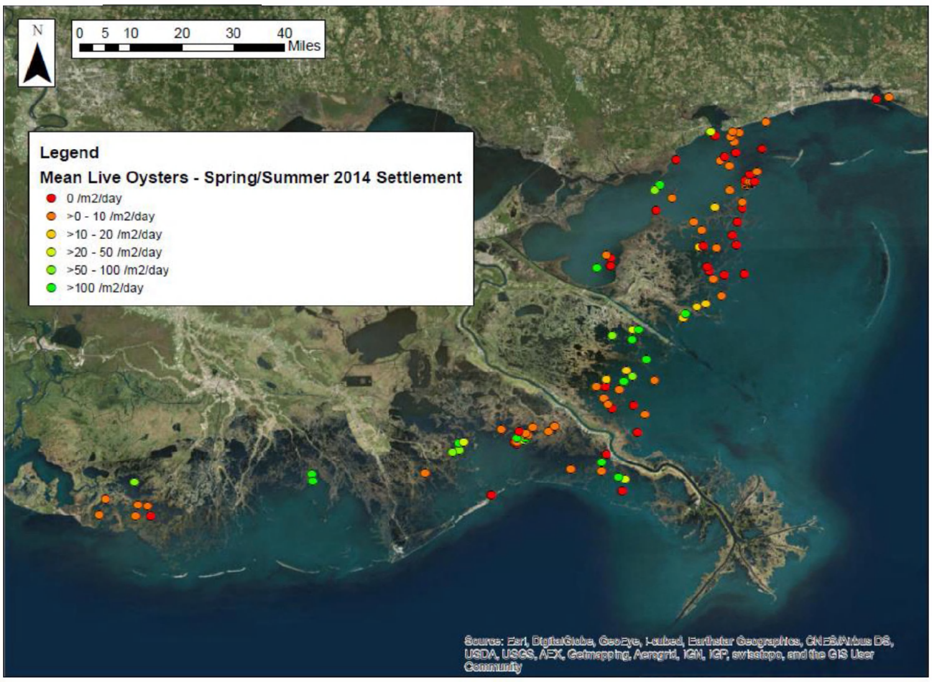

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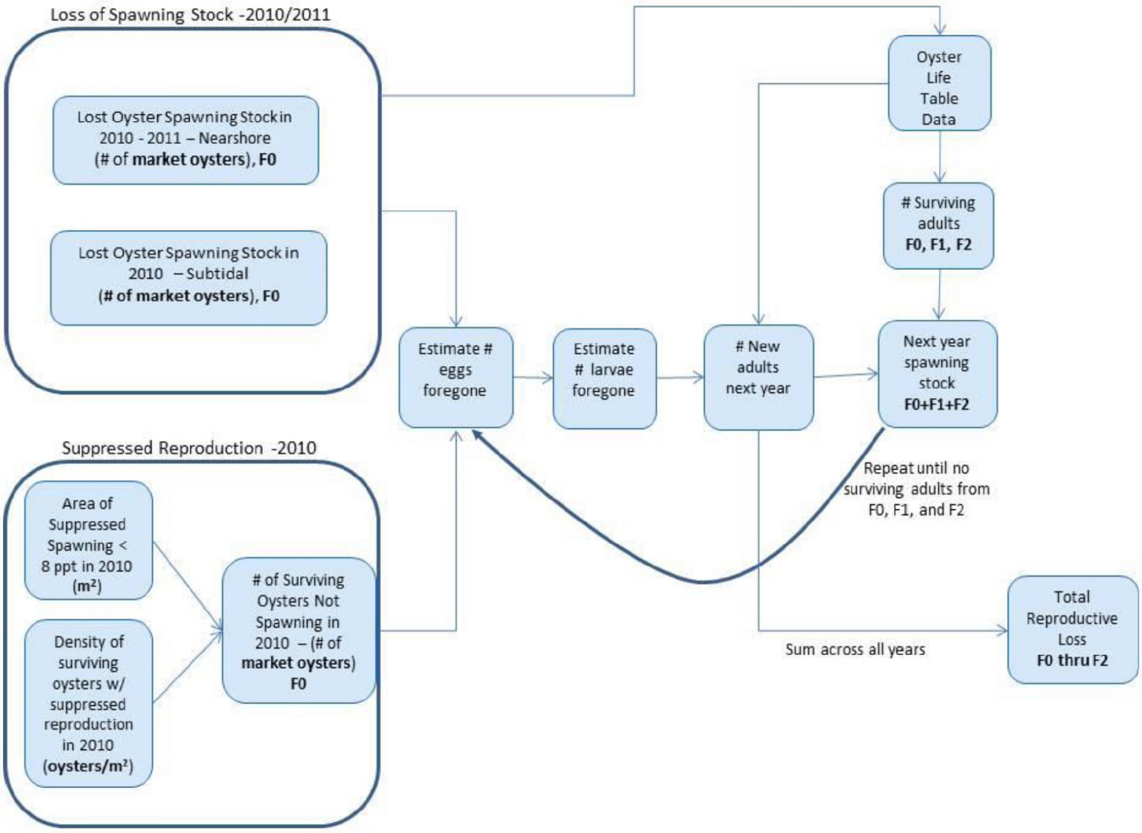
Exhibit 2. Flowchart of steps in oyster reproductive loss modeling.



Upper left box (Loss of Spawning Stock -2010/2011): The number of oyster killed and thus unable to reproduce (loss of spawning stock) in 2010-2011 was calculated from information on the number of adult (market size) oysters in both the nearshore and subtidal zones.

Bottom left (Suppressed Reproduction -2010): Oysters that were not killed did not reproduce at typical levels in 2010. Oysters living in areas where salinity was lower than 8ppt in 2010 were affected.

Exhibit 3. Oyster Percent Cover Strata.

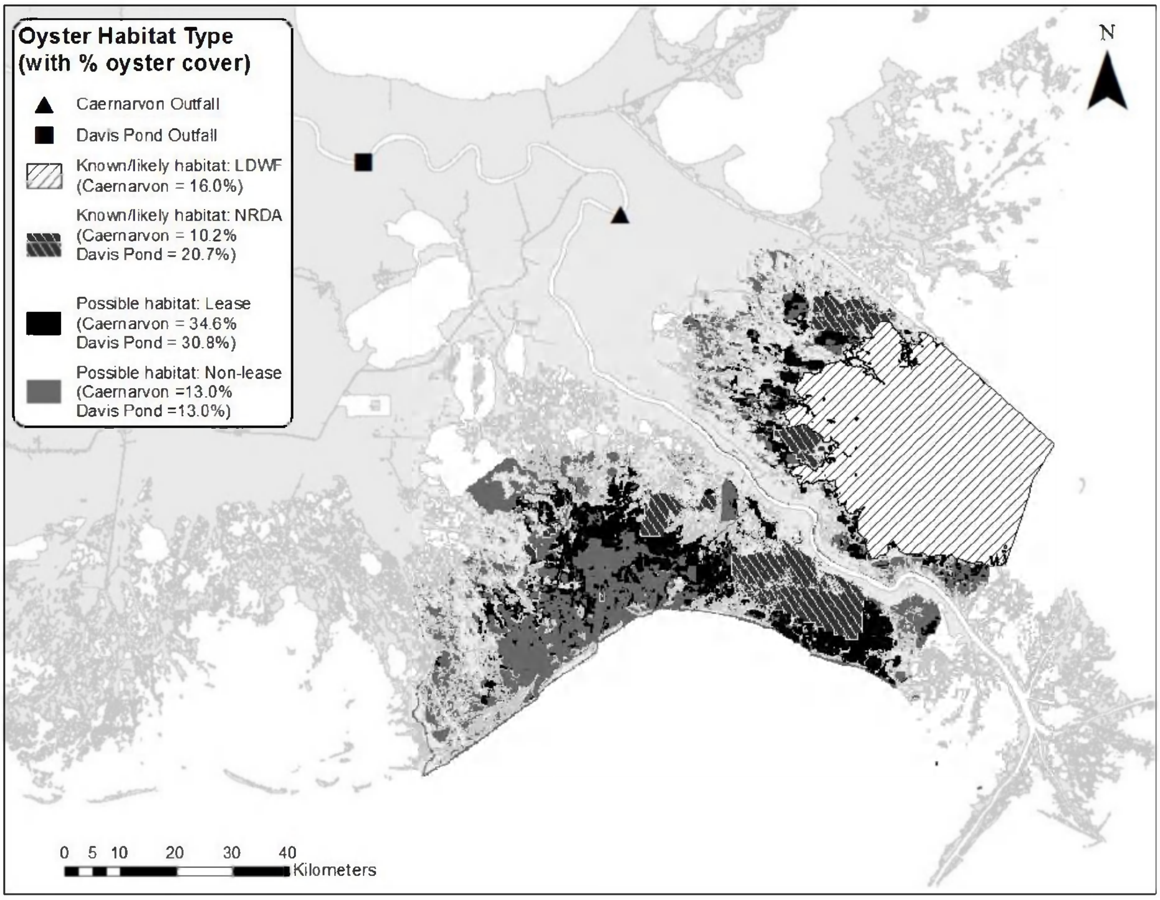


Exhibit 4. Area impacted by low salinity (Rouhani and Oehrig, 2015). The area affected by <5ppt for 30 additional consecutive days between April 27 and September 15, 2010 as compared with the historical baseline (2006-2009) is shown in pink. The area affected by <8 ppt daily for more than 30 total days between April 27 and September 15, 2010 is shown in black.

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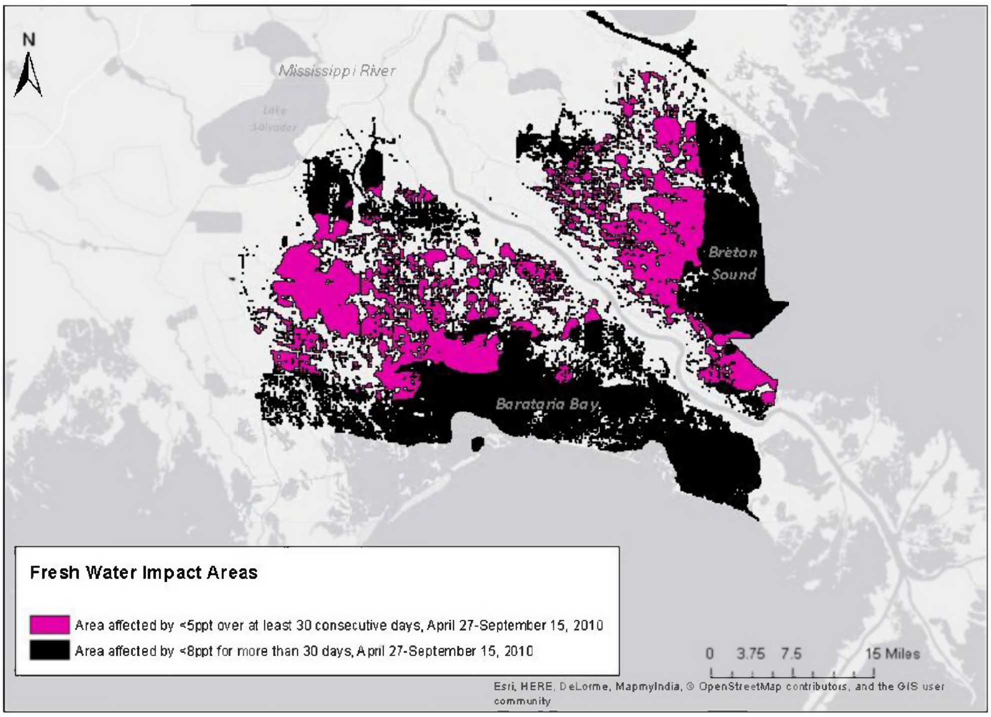

Exhibit 5. Reproductive Injury/Egg Loss Model Inputs.

INPUT (METRIC)	VALUE	SOURCE
Lost nearshore spawning stock (market equivalent oysters)	8,275,087[1]	Powers, S.P. et al. 2015b. Loss of Oysters as a Result of the Deepwater Horizon Oil Spill Degrades Nearshore Ecosystems and Disrupts Facilitation Between Oysters and Marshes.
Lost subtidal spawning stock[2] (market equivalent oysters)	NRDA spatial: 1,164,000,000 Nestier: 2,694,000,000 Fisheries Temporal: 3,169,000,000	Powers, S.P. et al. 2015a. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations.
Surviving spawning stock affected by low salinity[3] (market equivalent oysters)	FID: 27,932,343 Polygon: 696,196,314	Calculated using data from Powers, S.P. et al. 2015a. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations.
Percent of lost spawning stock that are female (%)	70[4]	National Oceanic and Atmospheric Administration. Oyster length and gender data from Mussel Watch Contaminant Monitoring Program. Obtained 2015.
Assumed minimum size of oyster at sexual maturity (mm)	75	Powers, S.P. (unpublished data)
Average female fecundity/year (eggs)	6,075,242[5]	Cox, C. and R. Mann (1992)
Fertilization rate (%)	25[6]	Powers, S.P. (unpublished data)
Survival to seed (%)	6.00E-09[7]	Rumrill, S.S. (1990)
Survival of seed to market (%)	56	Roman, H. and T. Hollweg. (2015). Development of Oyster Life Table and Application to Estimate DWH Oyster Injury Metrics. Technical Memo.
Percent survival each respective year after oysters mature to market size[8] (%)	Year 1: 100 Year 2: 60 Year 3: 36 Year 4: 22	

NOTES:

1. Market Size Equivalent (Direct injury by end of 2011 + recruitment forgone in 2012 onward due to lost habitat)

2. The two approaches (FID and Polygon) correspond with the approaches presented in Powers, S.P. et al. 2015a. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations.
3. The three approaches (Nestier Tray, FID and Polygon) correspond with the approaches presented in Powers, S.P. et al. 2015a. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations.
4. Calculated from Mussel Watch Contaminant Monitoring data collected during 2010-2011. This ratio excludes oysters of undetermined sex, since we cannot accurately assign a probability that undetermined oysters will be male or female.
5. Calculated as a weighted average of values in Cox, C. and R. Mann (1992), Table 3.
6. No known oyster fertilization studies.
7. Average survivorship for Crassostrea gigas and Ostrea edulis during initial year (365 days) after spawning from Rumrill, S.S. (1990), Table 3.
8. Deplete for four years assuming starting with a market size oyster and five year average lifespan.

Exhibit 6. Timeline for Reproduction Forgone Elements.

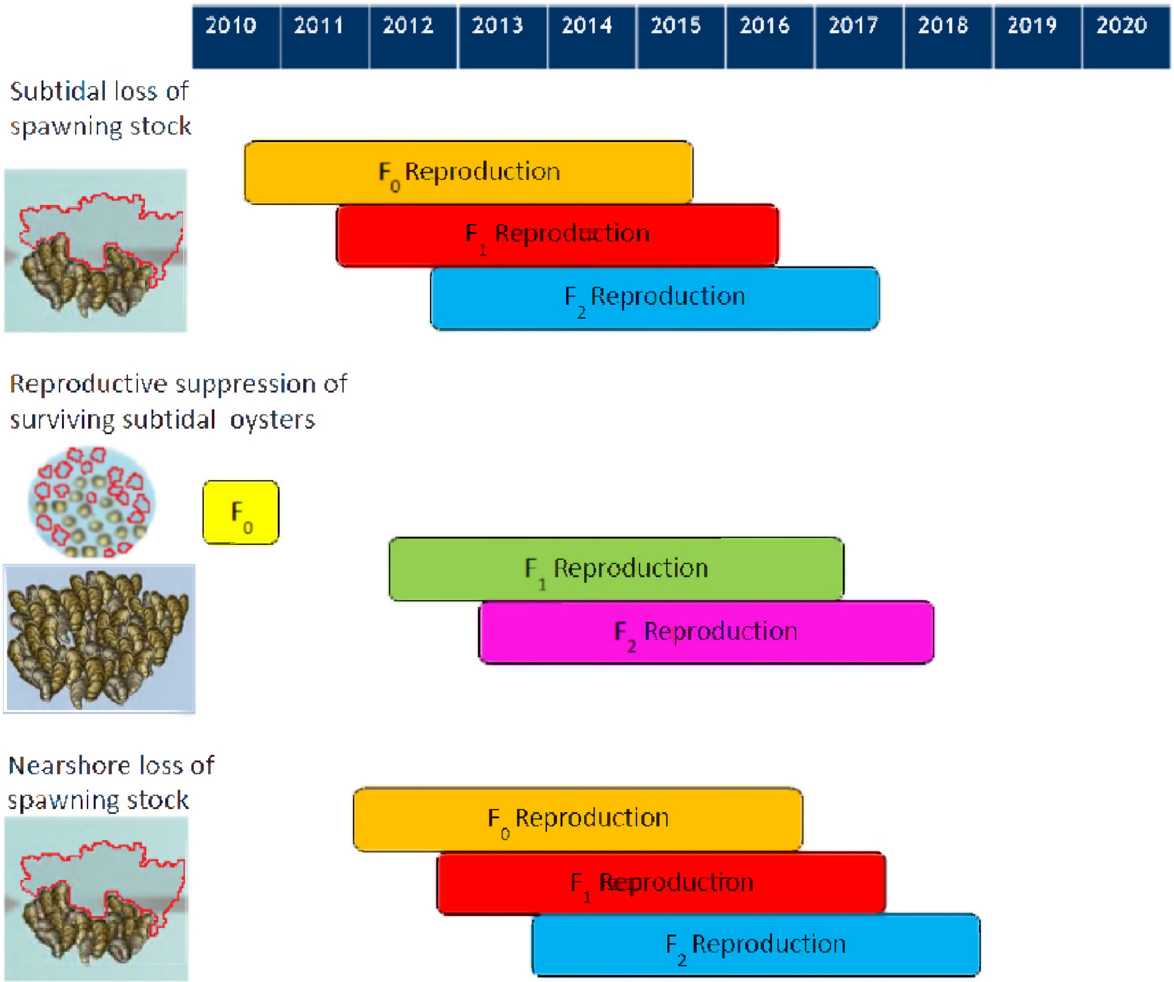

Exhibit 7. Annual Breakdown - Reproduction Forgone due to Oyster Spawning Stock Mortality in Nearshore and Subtidal Habitats.

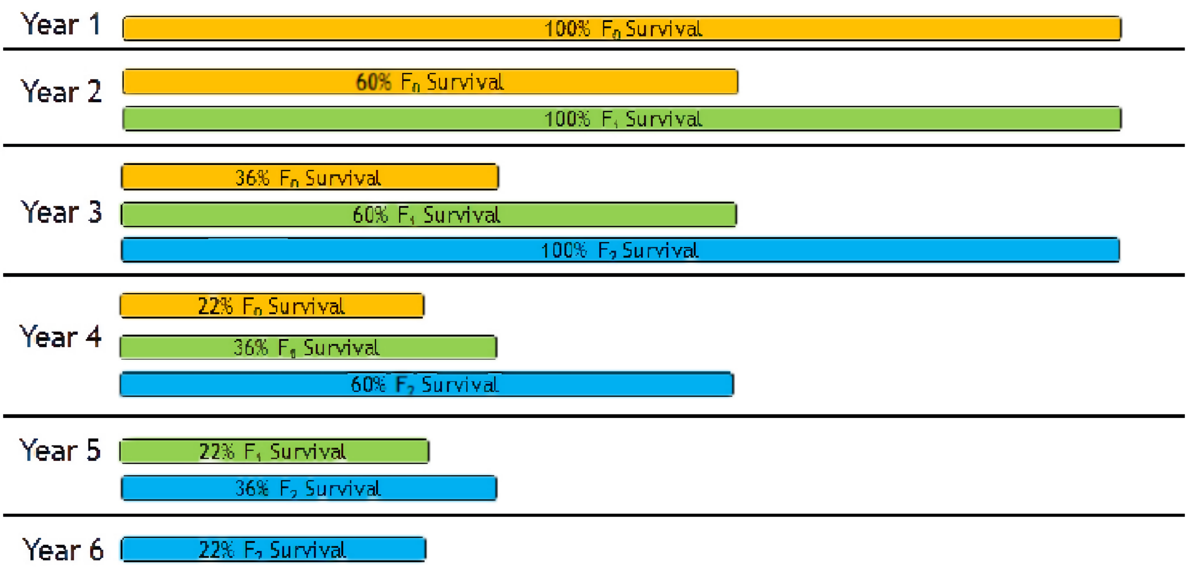

Exhibit 8. Annual Breakdown - Reproduction Forgone due to Suppressed Subtidal Oyster Reproduction in 2010.

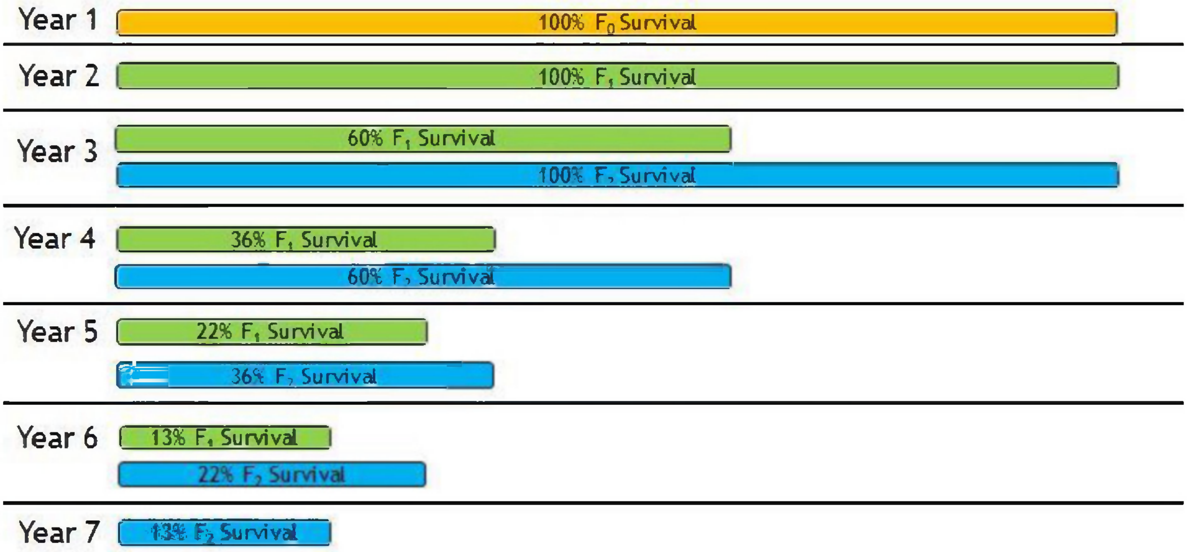

Exhibit 9. Quantity of oyster reproduction forgone due to lost spawning stock and suppressed reproduction.

HABITAT	REPRODUCTION FORGONE	AREA OF INJURY	PRIMARY ESTIMATE OF MARKET EQUIVALENT OYSTERS FORGONE[*] (10^6)	ESTIMATED RANGE OF MARKET EQUIVALENT OYSTERS FORGONE[**] (10^6)
Nearshore	Due to lost spawning stock 2010-2011	LA, MS, AL	9.7	N/A
	Due to loss of nearshore recruitment (annual-2012 onward)	LA, MS, AL	5.7 (per year)	N/A
Subtidal	Due to lost spawning stock	LA CSA 1S and 3	3,100	1,400 – 3,700
	Due to suppressed reproduction in surviving oysters	LA CSA 1S	180	N/A
		LA CSA 3	1,200	N/A
		Subtotal	1,400	N/A
	Subtidal Total		4,500	2,800 – 5,100

**Primary Estimate is based on measure of direct kill of subtidal spawning stock based on Nestier Tray injury analysis (Powers et al. 2015a).

**Range is based on alternative measures of direct kill of subtidal spawning stock (Powers et al. 2015a).

REFERENCES

Cox, C., and R. Mann. 1992. Temporal and Spatial Changes in Fecundity of Eastern Oysters, *Crassostrea Virginica* (GMELIN, 1791) in the James River, Virginia. J Shellfish *Res* 11(1):49-54.

Duke, R.W. Jr. 2008. Oyster survival and growth within the Barataria Estuary. MS Thesis, Nicholls State University, Thibodaux, LA.

Grabowski, J.H., S.P. Powers, H.Roman, and S. Rouhani. 2015. Impacts of the 2010 Deepwater Horizon Oil Spill and associated response activities on subtidal oyster populations in the Northern Gulf of Mexico. DWH NRDA Oyster Technical Working Group Report.

Murray, J., H. Roman, and J. Westerink. 2015. Development of Oyster Larval Transport Analysis (ADCIRC).DWH NRDA Oyster Technical Working Group Report.

National Oceanic and Atmospheric Administration. Oyster length and gender data from Mussel Watch Contaminant Monitoring Program. Obtained 2015.

Powers, S. P., J. H. Grabowski, H. Roman, A. Geggel, S. Rouhani, J. Oehrig, and M.C. Baker. 2015a. Consequences of Large Scale Hydrographic Alteration During the Deepwater Horizon Oil Spill on Subtidal Oyster Populations. DWH NRDA Oyster Technical Working Group Manuscript.

Powers, S.P., S, Rouhani, M.C. Baker, H. Roman, J.H. Grabowski, S.B. Scyphers, J. Murray, J.M. Willis, and M.W. Hester. 2015b. Loss of oysters as a result of the Deepwater Horizon Oil Spill degrades nearshore ecosystems and disrupts facilitation between oysters and marshes. DWH NRDA Oyster Technical Working Group Manuscript.

Roman, H. and T. Hollweg. 2015. Development of Oyster Life Table and Application to Estimate DWH Oyster Injury Metrics. DWH NRDA Oyster Technical Working Group Technical Report.

Rouhani and Oehrig, 2015. Methodology Used to Determine the Spatial Extent of Fresh Water Impact in Barataria Bay and Black/Bay Breton Sound Basins in 2010. DWH NRDA Oyster Technical Working Group Technical Report.

Rumrill, S. 1990. Natural Mortality of Marine Invertebrate Larvae. Ophelia 32(1-2):163-198.

Soniat, T. M., N. Cooper, E. N. Powell, J. M. Klinck, M. Abdelguerfi, S. Tu, R. Mann, and P.D. Banks. 2014. Estimating sustainable harvests of eastern oysters, *Crassostrea virginica*. Journal of Shellfish Research 33(2):381-394.